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# Electric Road Systems

Modelling & simulation research at the CSRF / University of Cambridge

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**D Ainalis, P Deshpande, J Miles, P Greening, C Thorne, D Cebon**



**ZEUS**

# Electric Road Systems

- An **Electric Road System (ERS)** is an economically attractive solution to decarbonise Heavy Goods Vehicles (HGVs) HGVs in the UK
- An ERS **reduces the battery capacity** needed for many journeys vs. “big-battery” trucks
- This reduces:
  - Vehicle cost, weight & efficiency
  - Embodied emissions
  - Peak loading on the electricity grid
- Objectives:
  - Techno-economic comparison with BEV/FCEV
  - Quantify impact on battery sizes
  - Country-agnostic ERS investment model



# **UK ERS research overview**



# 2020 CSRF White Paper

 **SRF** | THE CENTRE FOR SUSTAINABLE ROAD FREIGHT

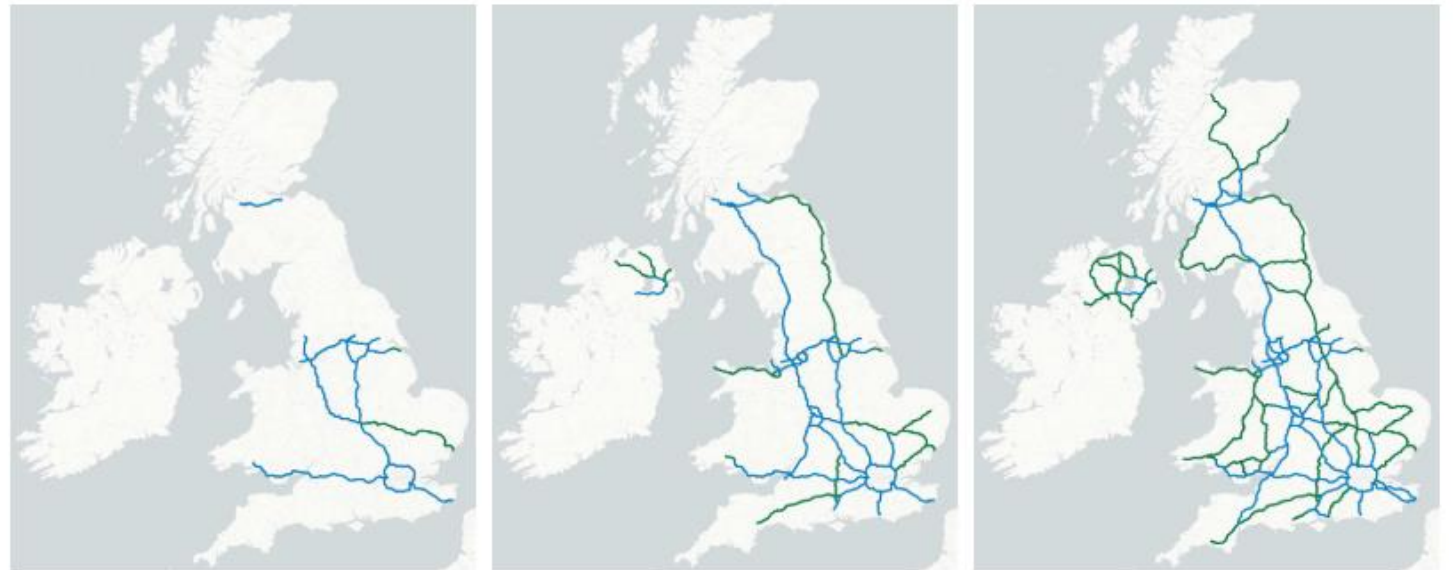
**White Paper**  
Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost



**Technical Report CUED/C-SRF/TR17**  
July 2020  
D.T. Ainalis, C. Thorne, and D. Cebon


This White Paper has been produced as part of the Centre for Sustainable Road Freight (EPORC grant number EP/R035146/1). Further details about the Centre are available at: <http://www.csrfd.ac.uk>

- Three ERS “phases” / topographies identified
- Infrastructure cost of £19.4 billion over 8 years
- Attractive payback period for operators & infrastructure providers
- Government recoups 100 % of diesel tax revenues



Ainalis, D. T., Thorne, C., & Cebon, D. (2020). White Paper: Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost. Technical Report CUED/C-SRF/TR17. Centre for Sustainable Road Freight.

# 2021/2022 UK ERS demonstrator feasibility study



**UK Electric Road System**  
National System Definition and Roll-Out  
Feasibility Report

April 2022

Authors: Costain, Siemens Mobility, SRF, Powerlines, Arup, Centre for CI Planning

Available online at [www.sciencedirect.com](https://www.sciencedirect.com)

ScienceDirect  
Transportation Research Procedia 09 (2022) 300-300

Transportation Research  
Procedia  
[www.elsevier.com/locate/procedia](https://www.elsevier.com/locate/procedia)

Transport Research Arena (TRA) Conference  
Vehicle and charging requirements for an electrified road freight system demonstrator in the UK  
Christopher de Saxe<sup>a,\*</sup>, Daniel Ainalis<sup>a</sup>, John Miles<sup>a</sup>, Phil Greening<sup>a</sup>, Adam Gripton<sup>a</sup>, Christopher Thorne<sup>a</sup>, David Cebon<sup>a</sup>

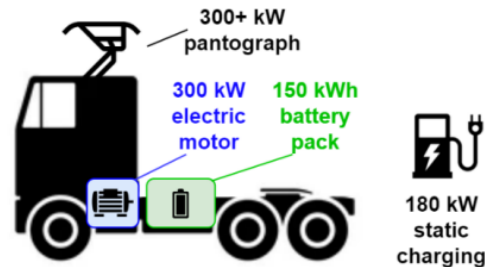
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<sup>b</sup>University of the Witwatersrand, School of Mechanical, Industrial & Aeronautical Eng., 1 Jan Smuts Ave, Johannesburg 2000, South Africa  
<sup>c</sup>Heriot Watt University, Edinburgh Business School, Edinburgh EH14 4AS, United Kingdom  
<sup>d</sup>Trang Consultancy Ltd, Tring High Street, Hemel Hempstead, United Kingdom

**Abstract**  
The UK has set into law a target reduction of greenhouse gases of 78% by 2035 and 100% by 2050. Heavy Goods Vehicles (HGVs) represent 16% of UK road transport emissions are one of the 'difficult-to-decarbonise' sectors owing to their large mass and range requirements. An Electric Road System (ERS) with overhead charging wires presents an attractive solution to rapidly decarbonise HGVs at minimal cost and without the need for megawatt-scale batteries. In this work, we investigate some of the technical requirements for a proposed UK ERS demonstrator comprising 25 km of ERS on the M180 motorway in North Lincolnshire, including battery size and static charging infrastructure. A range of theoretical journey scenarios were considered, using simulated journeys and a detailed dynamic model of a 44 t ERS electric lorry. The results indicate the need for three vehicle types: a 150 kWh 'small-battery' ERS vehicle, a 500 kWh 'medium-battery' ERS vehicle, and a 300 kWh battery variant with a range extender for journeys with significant off-ERS driving requirements during the demonstrator.

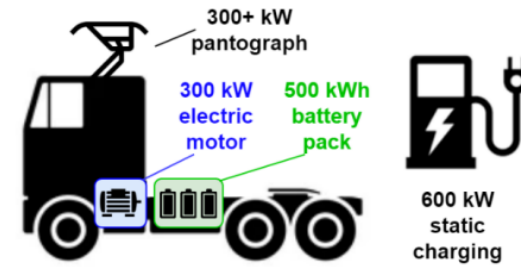
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Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference  
Keywords: Electric Road System; Road Freight Transport; Decarbonisation; Greening Freight Transport

**1. Introduction**  
In its sixth Carbon Budget, the UK set into law a target reduction of greenhouse gas (GHG) emissions of 78% by 2035 relative to 1990 levels (CCC, 2020), and reaffirmed its dedication to net zero emissions by 2050 (HM Government, 2019). By sector, transport is the largest contributor to GHG emissions in the UK, accounting for 27% of emissions in 2019, and of this road transport carries the biggest share of 91% (DOT, 2021). Heavy Goods Vehicles (HGVs) are particularly over-represented, responsible for 16% of road transport emissions while contributing 5% of vehicle kilometres travelled (DOT, 2021). While full battery electric vehicles (BEVs) seem set to become the *de facto*

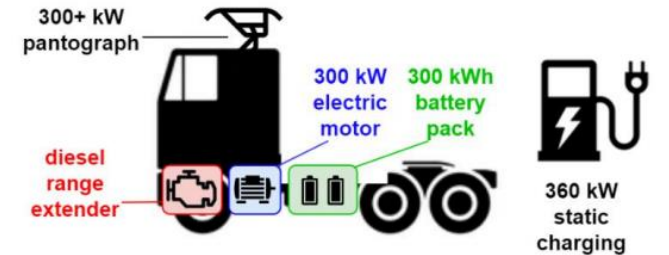
2102-1463 © 2022 The Authors. Published by ELSEVIER B.V. This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0/>)  
Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference



'Type 1' vehicle: Small battery



'Type 2' vehicle: Medium battery



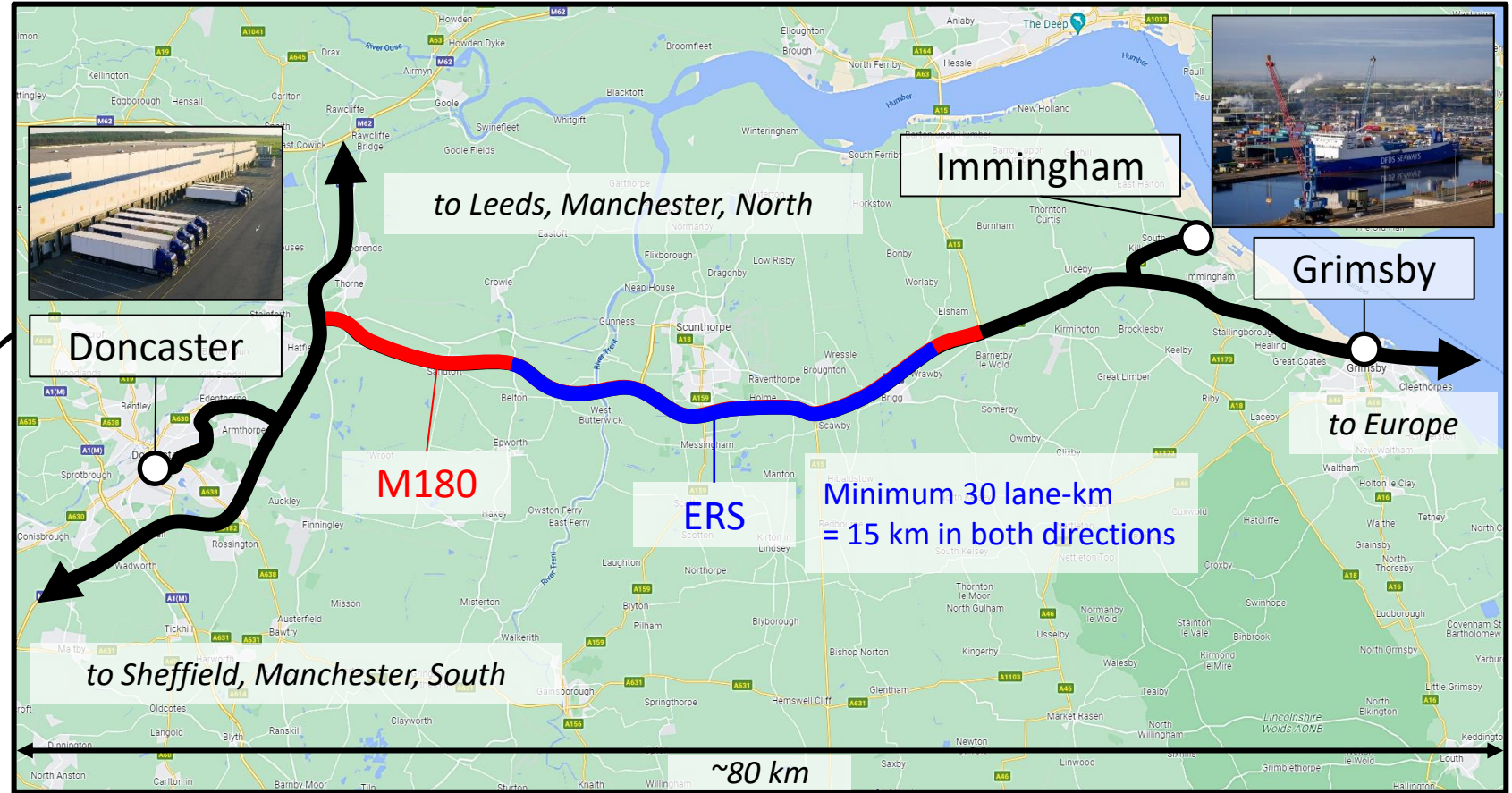
'Type 3' vehicle: Range-extended

- National system specification, cost & delivery plan
- Embodied carbon emissions study
- Design of a 30 lane-km demonstrator on the M180
- Demonstrator vehicle and charging needs identified

C de Saxe, D Ainalis, J Miles, P Greening, A Gripton, C Thorn, D Cebon, "Vehicle & charging requirements for an electrified road freight system demonstrator in the UK", Transport Research Arena, Lisbon, 14-17 Nov. 2022



# M180 demonstrator



# 2022 Technoeconomic comparison with HFCEV

Research in Transportation Business & Management 48 (2022) 100914

Contents lists available at ScienceDirect

Research in Transportation Business & Management

journal homepage: [www.elsevier.com/locate/rtbm](http://www.elsevier.com/locate/rtbm)

Technoeconomic comparison of an electric road system and hydrogen for decarbonising the UK's long-haul road freight

Daniel Ainalis<sup>a,\*</sup>, Chris Thorne<sup>b</sup>, David Cebon<sup>a</sup>

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ARTICLE INFO ABSTRACT

**Keywords:** Sustainable road freight; Electrification; Hydrogen; Electric road system; Heavy goods vehicles; Technoeconomic analysis

Long-haul Heavy Goods Vehicles (HGVs) are a significant source of carbon emissions, accounting for around 5% of the UK's total. If the UK is to meet its net zero mandate, it is vital to have a zero-emissions alternative to the traditional diesel-powered HGVs that is cost-effective and widespread in the 2040s. This paper presents a technoeconomic comparison of two solutions for decarbonising long-haul heavy goods vehicles in the UK: electric HGVs with an electric road system (overhead catenary) along the major road network, and fuel cell HGVs with public refuelling stations supplying green hydrogen. The results of the technoeconomic analysis show that overhead catenaries and compatible HGVs are the more energy-efficient and cost-effective solution to decarbonise the UK's long-haul road freight network and would provide both the infrastructure provider and fleet operators with competitive payback periods. With this approach, there is a potential to reclaim 30–80% of the diesel tax revenue currently earned by the UK government from HGVs, depending on the price of electricity. Conversely, the green hydrogen solution will require substantial government subsidies, particularly during the 2030s, to encourage fleet operators to purchase and use hydrogen fuel cell HGVs.

**1. Introduction**

The UK's Climate Change Act introduced legislation in 2008 to reduce its Greenhouse Gas (GHG) emissions in 2050 by 80% compared to 1990, and was revised in July 2019 to reach net zero emissions by 2050 (UK Government, 2008). Achieving net zero is a considerable challenge and requires wholesale changes to all facets of the energy system. One sector that requires substantial changes is surface transport – vital to the economy but currently the largest GHG emitting sector in the UK as shown in Fig. 1, accounting for 25% of UK emissions in 2018 (DBES, 2021). This increase is due not only to rising transport demand offsetting efficiency gains, but also the decarbonisation progress made in other sectors, notably in power generation as the UK electricity grid transitions from coal to natural gas and renewables.

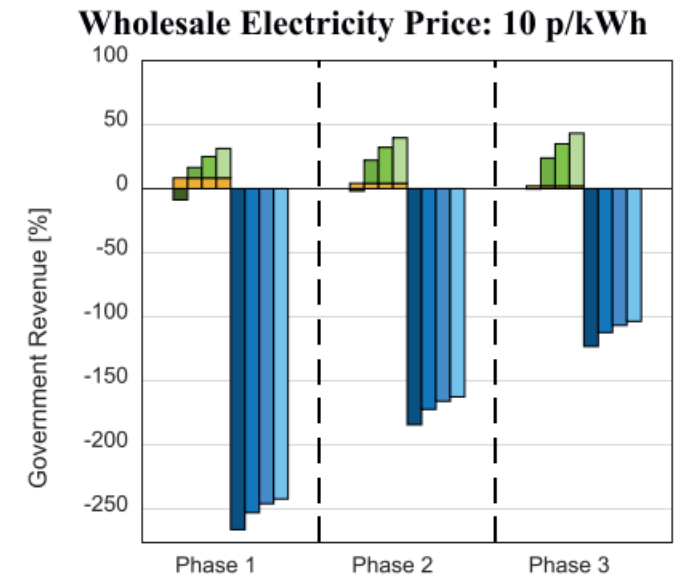
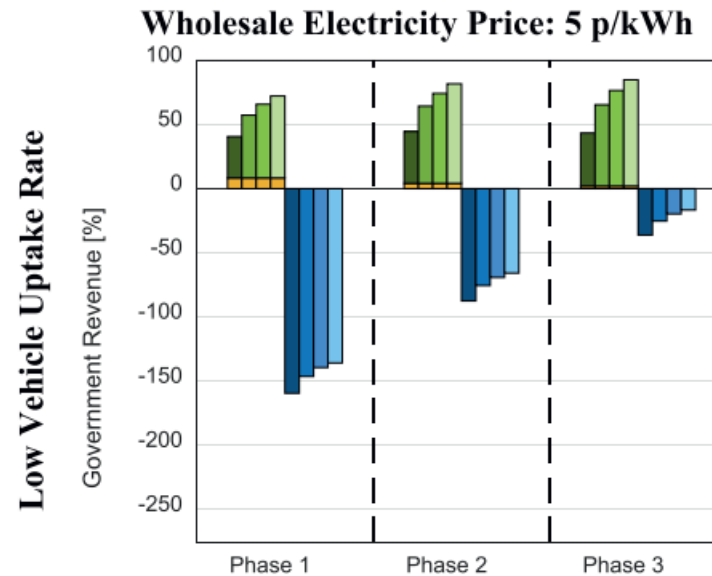
To decarbonise freight transport, there has been a significant increase in the electrification of light duty urban delivery vehicles in recent years. While initially limited to vans and home delivery vehicles, there are an increasing number of larger Battery Electric Vehicles (BEVs) available such as delivery vehicles up to 26 t, buses, and refuse collection vehicles. There are numerous reasons why BEVs are well-suited to urban logistics. The daily milages of these vehicles are relatively low (typically <100 km), which reduces the battery size, mass, and cost to acceptable levels without disrupting operations. As they operate in urban areas where they frequently stop and start, the ability to reuse electricity through regenerative braking provides a significant improvement in energy efficiency. It is expected that BEVs for urban delivery will become widespread in the UK over the next 10 years, particularly due to the pressure of air quality regulations in cities (clean air zones). Urban and regional delivery accounts for around one-third of all road freight tonne-km in England, with the remaining two-thirds of long-haul freight primarily largely travelling on the Strategic Road Network (SRN) (Pothof, 2013). Deploying BEVs for long-haul Heavy Goods Vehicle (HGV) operations has several challenges due to significant quantities of power and energy required for commercial operations (discussed in the following section in further detail). These HGVs currently produce around 5% of the UK's total GHG emissions alone, and so finding a suitable solution to decarbonise long-distance HGVs is imperative to achieve net zero (DBES, 2021).

Several technologies have been proposed to decarbonise the long-haul road freight sector. These include BEVs with large batteries, BEVs supported by an Electric Road System (ERS), hydrogen, biofuels, and synthetic fuels. An evaluation of the various powertrain solutions for

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<https://doi.org/10.1016/j.rtbm.2022.100914>  
 Received 29 December 2021; Received in revised form 17 October 2022; Accepted 23 November 2022  
 Available online 9 December 2022  
 2210-5395/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

- Extension and formalization of the white paper study
- Confirms beneficial economics of ERS

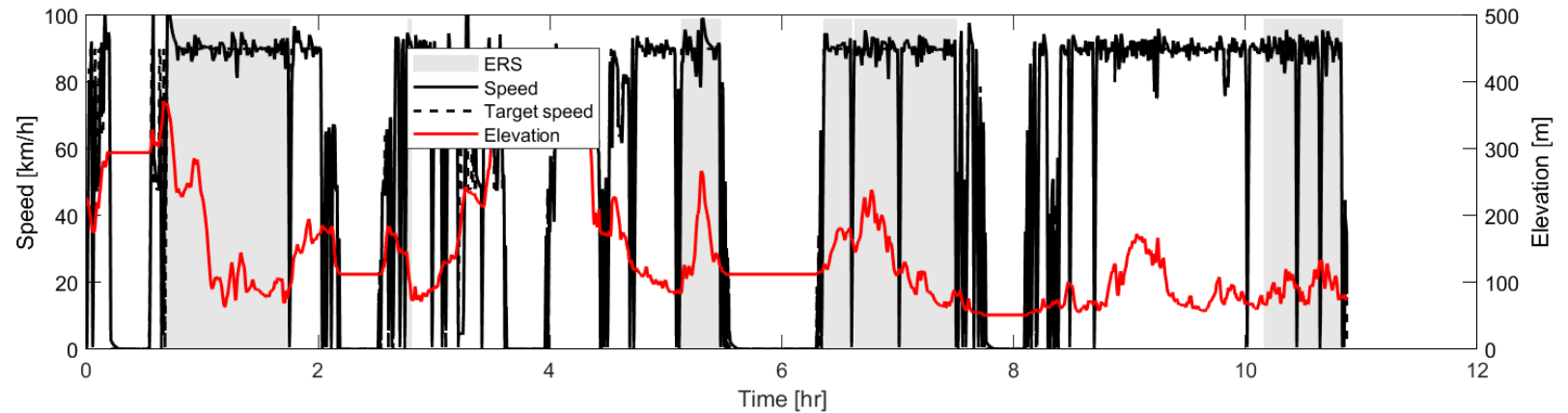


Ainalis, D., Thorne, C., & Cebon, D. (2022). Technoeconomic comparison of an electric road system and hydrogen for decarbonising the UK's long-haul road freight. *Research in Transportation Business & Management*, 100914.



# 2023 ERS vs “big-battery” simulations

- Validated driving cycle simulation model
- Real-world edge-case logistics journeys
- Battery sizes determined for a range of charging scenarios



C de Saxe, D Ainalis, J Miles, P Greening, A Gripton, C Thorne, D Cebon, "Battery and charging requirements for a UK electric road freight system", *Transportation Engineering*, vol. 14, pp. 100210, 2023.

Transportation Engineering 14 (2023) 100210

Contents lists available at ScienceDirect

Transportation Engineering

ELSEVIER journal homepage: [www.sciencedirect.com/journal/transportation-engineering](http://www.sciencedirect.com/journal/transportation-engineering)

### An electric road system or big batteries: Implications for UK road freight

Christopher de Saxe<sup>a,b,\*</sup>, Daniel Ainalis<sup>a</sup>, John Miles<sup>a</sup>, Philip Greening<sup>c</sup>, Adam Gripton<sup>a</sup>, Christopher Thorne<sup>d</sup>, David Cebon<sup>a</sup>

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<sup>c</sup> Heriot Watt University, Edinburgh Business School, United Kingdom  
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**ARTICLE INFO**

**ABSTRACT**

**Keywords:** Electric road system; Heavy goods vehicles; Battery electric vehicles; Charging infrastructure

An Electric Road System (ERS)—comprising a network of overhead cables to charge Heavy Goods Vehicles (HGVs) via a pantograph pick-up—is a cost-competitive solution to rapidly decarbonise the UK road freight sector. A major benefit over conventional battery electric HGVs is the reduction in battery capacities needed to fulfill logistics needs. In this study, we develop a detailed vehicle simulation model and use it to calculate the battery capacity requirements of real UK logistics journeys against a range of ERS network sizes and on-route static charging options. The results show that, averaged over all static charging scenarios, ERS reduces battery sizes by 41 %, 62 %, and 75 % for the ‘Light’ (2,750 km), ‘Medium’ (5,500 km) and ‘Heavy’ (8,500 km) ERS scenarios. Of the static charging scenarios, drop-off charging is shown to be more effective than rest stop charging at reducing battery sizes.

**Introduction**

**Background**

The climate crisis is arguably the defining challenge of our age. The Intergovernmental Panel on Climate Change (IPCC) predicts the earth’s average temperature will likely exceed the critical threshold of 1.5 °Celsius within the early 2030s relative to pre-industrial levels [32]. This can only be averted through urgent and drastic interventions in the most carbon-intensive sectors of society. In the UK, while the energy sector has been steadily decarbonising over the last 20 years, emissions from the transport sector have remained relatively stable, such that transport now represents the largest contributor to greenhouse gas (GHG) emissions in the UK at 27 % of the total in 2019 [17]. Road transport carries the biggest share of transport emissions at 91 %. Heavy Goods Vehicles (HGVs) account for 16 % of road transport emissions despite accounting for only 5 % of vehicle kilometres travelled [17].

The UK government has committed in law to a reduction of GHG emissions of 78 % by 2035 relative to 1990 levels [11], with a target of net zero emissions by 2050 [27]. As part of this plan, it has pledged to end the sale of non-zero emission HGVs by 2040, with those 26 t or less being phased out by 2035 [18]. The HGV sector is one of the most ‘difficult-to-decarbonise’ sectors [10], given the vehicles’ significant power and energy requirements. (The total energy footprint of HGVs in the UK is estimated to be 8.2 gigawatts [12], around two and a half times the planned capacity of the UK’s Hinkley Point C nuclear power station.) These targets present a significant challenge for the sector, and drastic solutions will be required at scale in a relatively short timeframe.

Recent trends and research have highlighted three likely solutions for zero-emission HGVs:

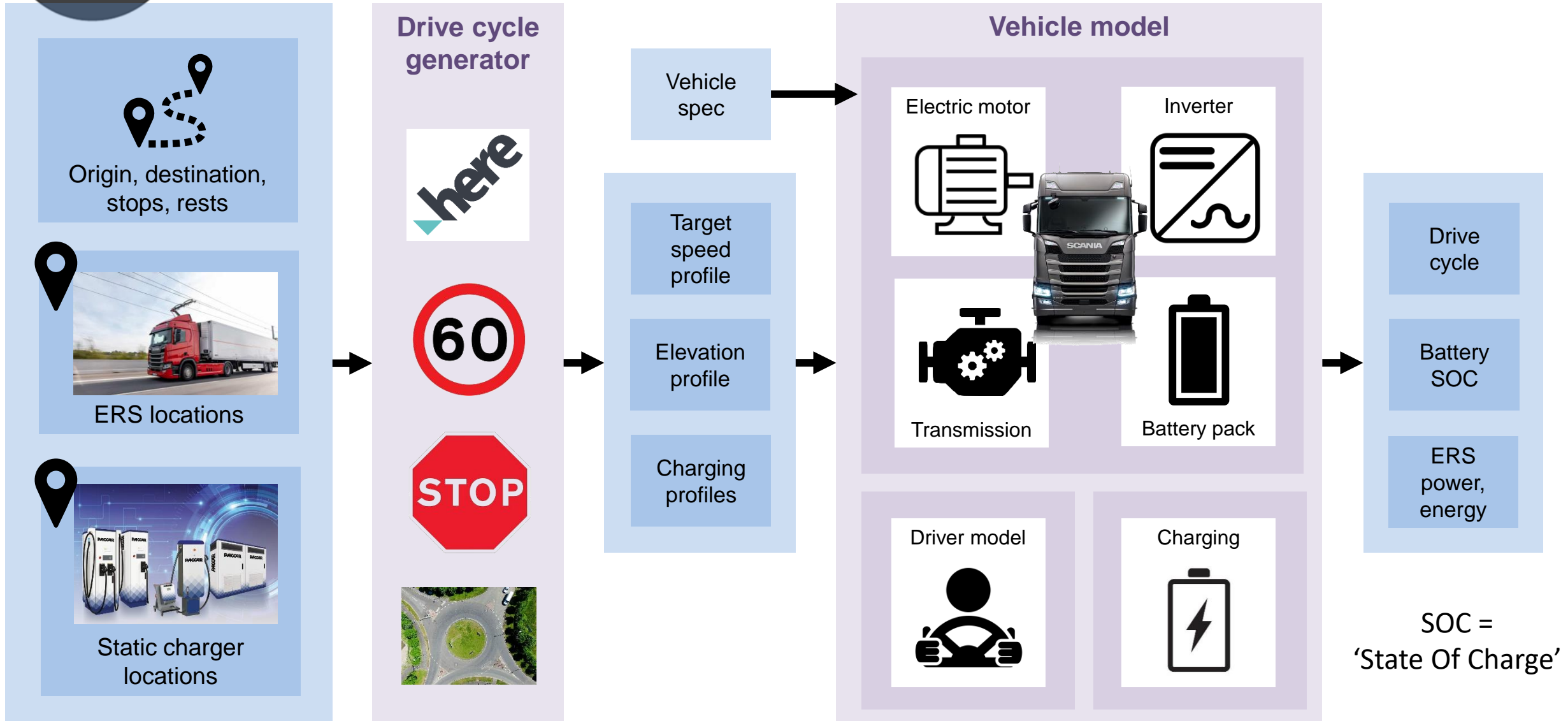
- ‘Big-battery’ electric vehicles (B-BEVs), with battery capacities of the order of 500–1000 kWh, and a supporting network of high-powered static chargers potentially including those which meet the ‘Megawatt Charging System’ (MCS) standard (1000+ kW). Examples of first-generation ‘big-battery’ BEVs include the 44-tonne-rated Volvo FMX electric (up to 540 kWh, with charging at up to 250 kW) [57], the 65-tonne-rated Scania (up to 624 kWh, with charging at up to 375 kWh) [47], and the 37-tonne-rated Nikola Tre (733 kWh, with charging up to 350 kW) [59].
- Hydrogen fuel cell electric vehicles (FCEVs), with large fuel cell stacks, hydrogen tanks (storing either liquid or gaseous hydrogen), and relatively small battery packs. A near-production example is the 37-tonne-rated Nikola Tre FCEV, which is reported to have 70 kg of

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<https://doi.org/10.1016/j.treng.2023.100210>  
Received 13 April 2023; Received in revised form 26 August 2023; Accepted 19 October 2023  
Available online 24 October 2023  
2666-691X/© 2023 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

# Driving cycle simulations

# Detailed drive cycle simulation model





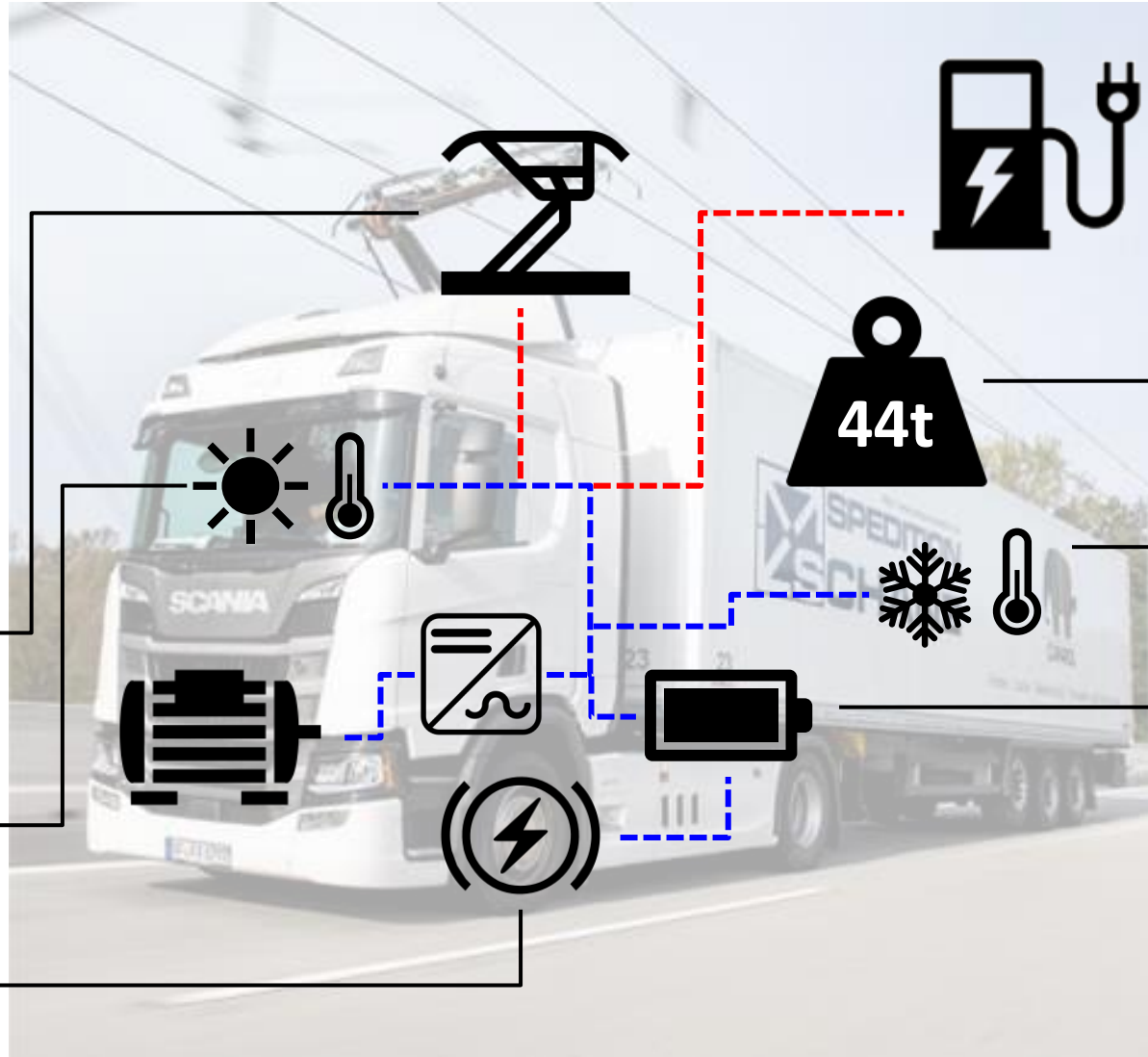
# Detailed drive cycle simulation model

- Based on (Madhusudhanan & Na, 2020)
- Updated in consultation with Scania & Siemens.
- Validated against German ERS data with 1.3% error.

ERS supplies power needs and charges battery at **~150 kW**

Cabin heating (1-3 kW)

Regenerative braking



Static charging:  
**100 kW @ depots**  
**600 kW @ drop/rest**

Maximum permitted combination mass **44t**

Trailer refrigeration (8-16kW on/off)

Useable state-of-charge = 20-100%



**SCANIA**

**SIEMENS**

# **Driving cycle simulations**

Scenarios & journeys



# ERS scenarios

ERS network



Length (2-way):

2,750 km

5,500 km

8,500 km





# Journeys

## Tramping day 2

Wetherby (overnight), Newton Stewart, Girvan, Irvine, Tirril

## Tramping day 1

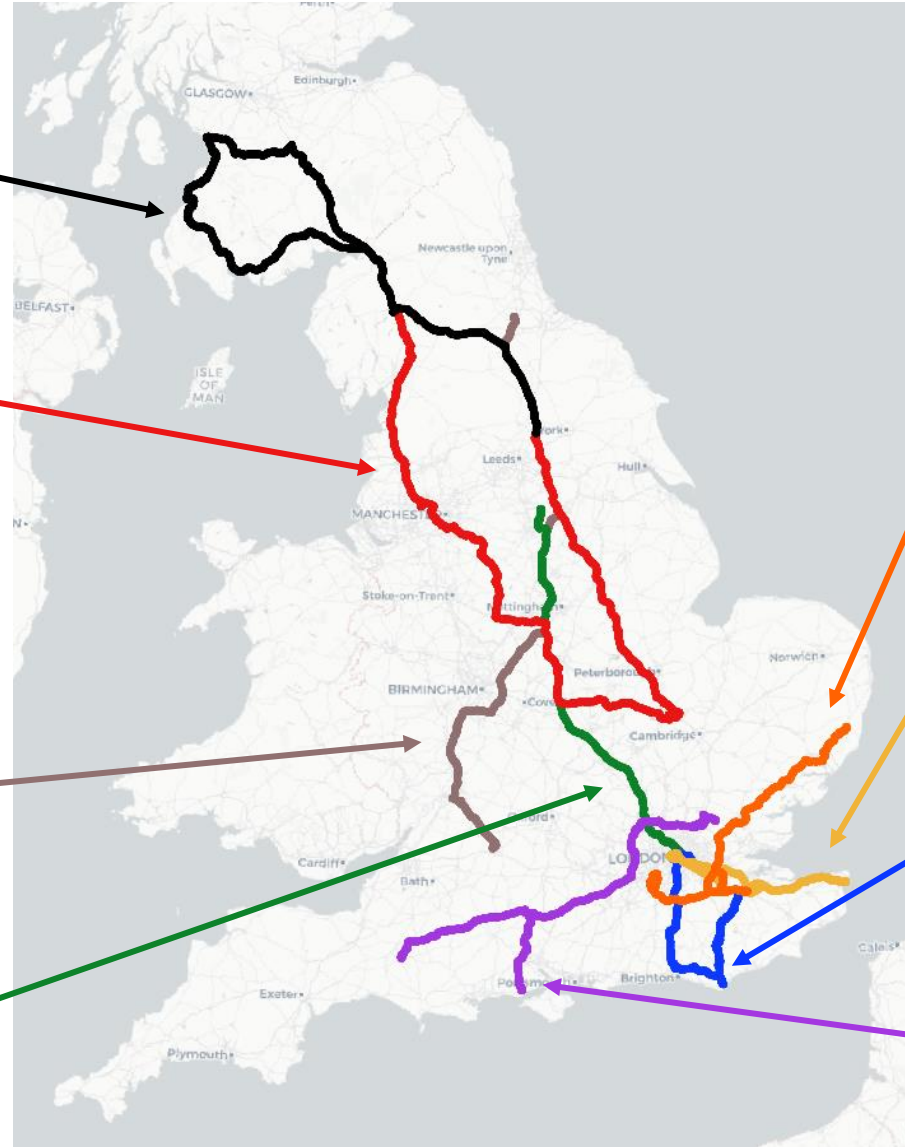
Tirril, Shap, Bolton, Buxton, St Ives (Cams), Wetherby (overnight)

## Warehouse-to-warehouse

Swindon to Newton Aycliffe

## Warehouse-to-warehouse

Royal London Hospital to Wath-upon-Dearne



## Summary

**8 trips** across England  
Distances of **290 – 690 km**  
Durations of **3.6 – 15 hr**

## Multi-drop

Aylesford, Saxmundham, Woodbridge, Kingston-upon-Thames, Aylesford

## Multi-drop

Aylesford, Bloomsbury, Kensington Gardens, Ramsgate, Aylesford

## Multi-drop

Aylesford, Eastbourne, Lewes, Marylebone, Aylesford

## Multi-drop

Andover, Lymington, Romsey, Andover, Yeovil, Ongar, Andover

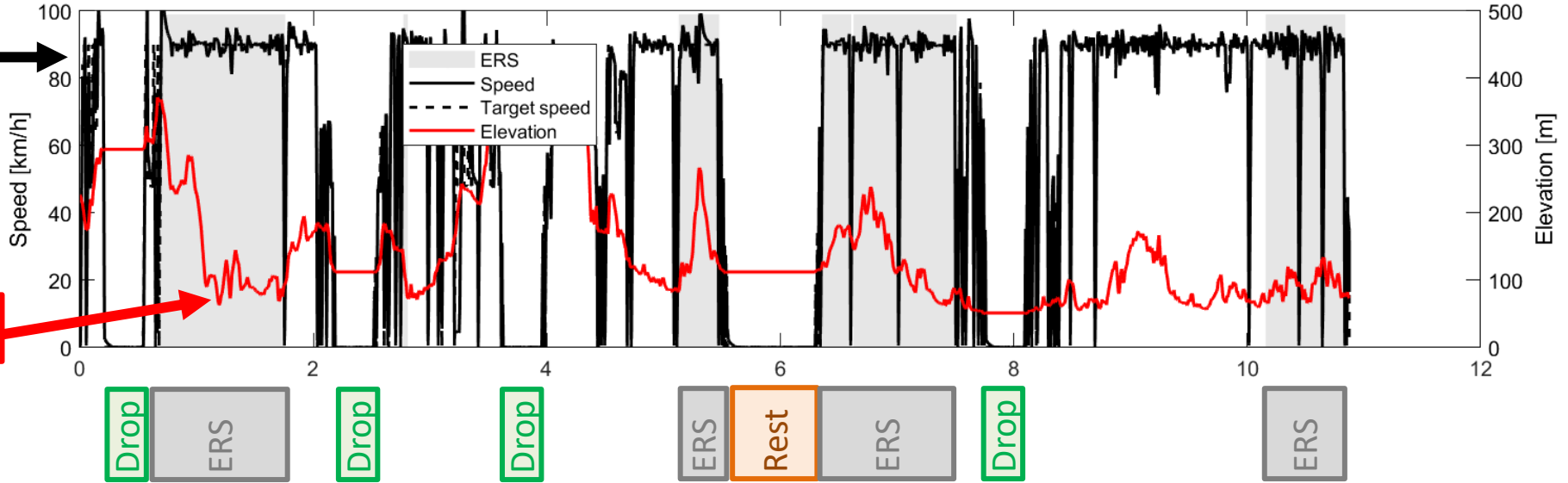
# **Driving cycle simulations**

## Results



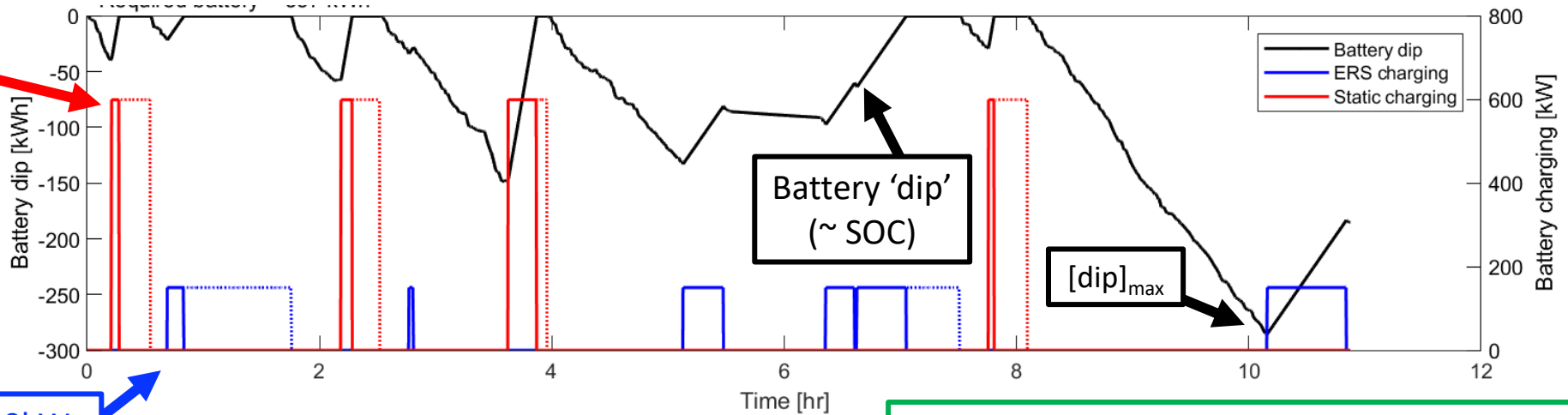
# Drive cycle (Tramping Day 1, ERS L + drop-off charging)

Speed profile



Elevation profile

Static charging @ 600kW



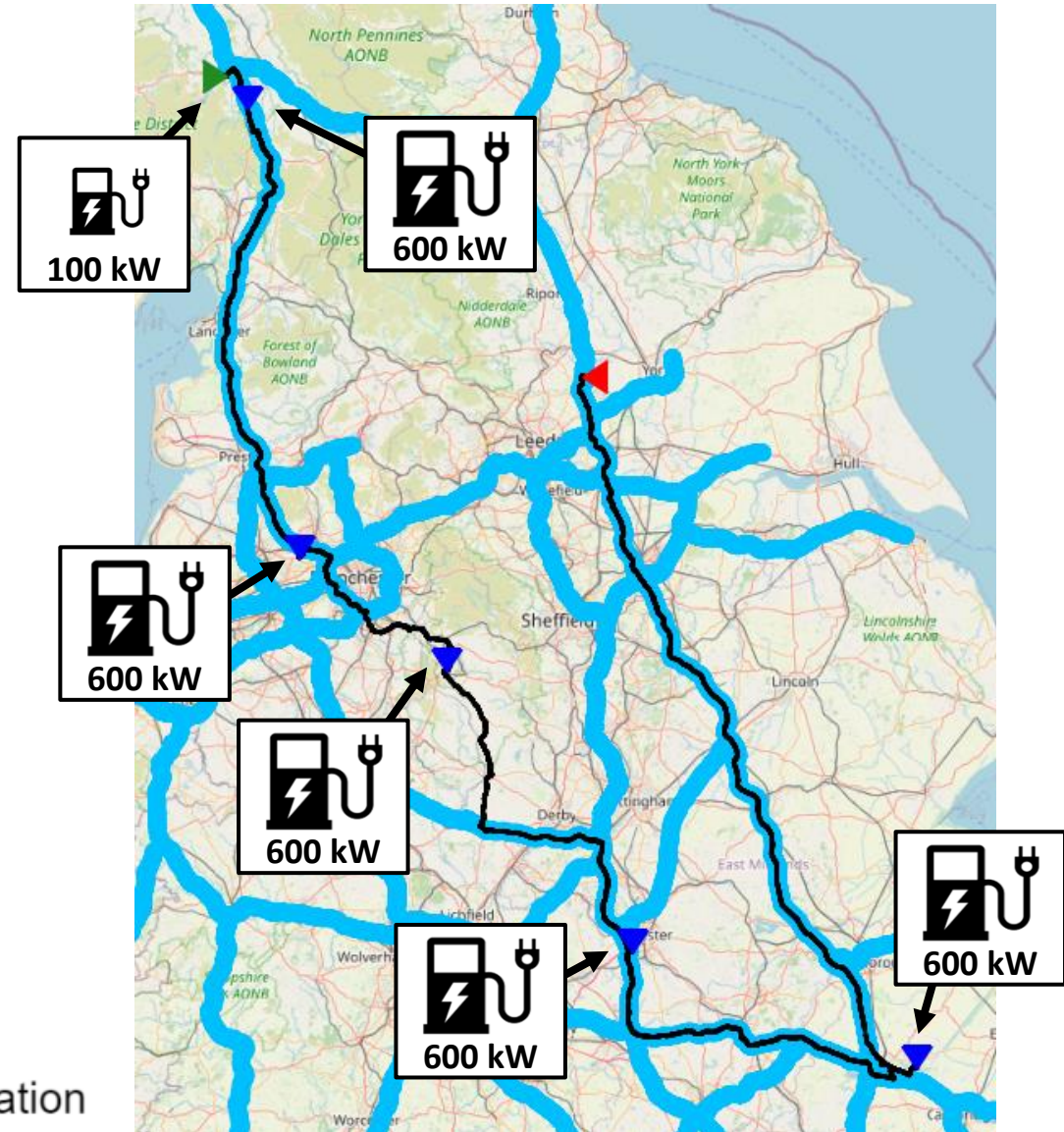
ERS charging @ 150kW

Required battery capacity =  $| [dip]_{max} | / 80\% = 357 \text{ kWh}$

# Journey matrix (battery sizes) (Tramping Day 1)

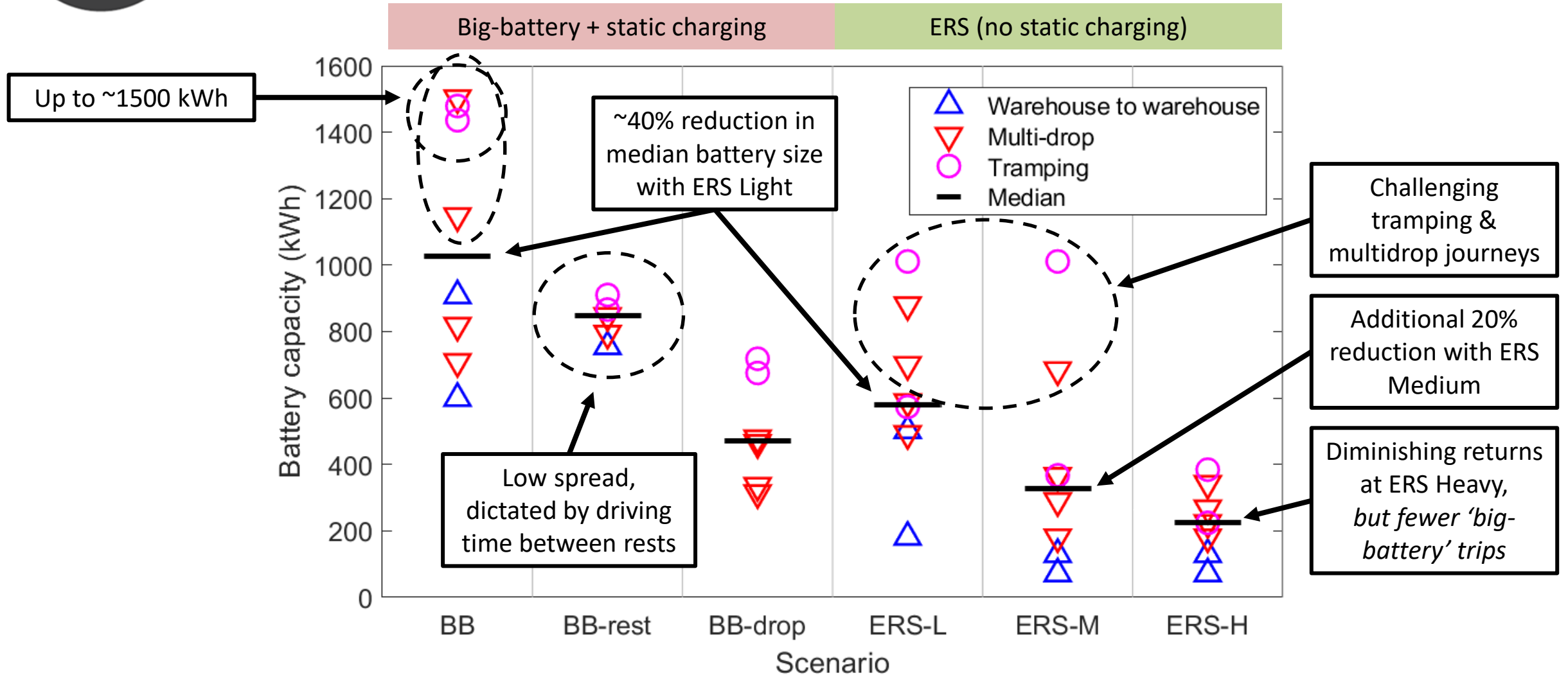
Tirril → Shap → Bolton → Buxton → Leicester (rest)  
 → St Ives (Cambs) → Wetherby (overnight)

Tramping Day 1		ERS topography			
		None	L	M	H
Static charging	None	1479	573	367	224
	Drop-off	718	357	167	122
	Rest stops	910	429	367	224



▶ Origin    ▼ Drop/rest    ◀ Destination

# ERS vs. 'big-battery' scenarios





## Battery reductions relative to 'big-battery' scenario

Ave. battery size reductions (%)		ERS topography		
		L	M	H
Static charging	None	43%	64%	79%
	Drop-off	38%	58%	71%
	Rest stops	42%	64%	74%
Average reduction:		41%	62%	75%

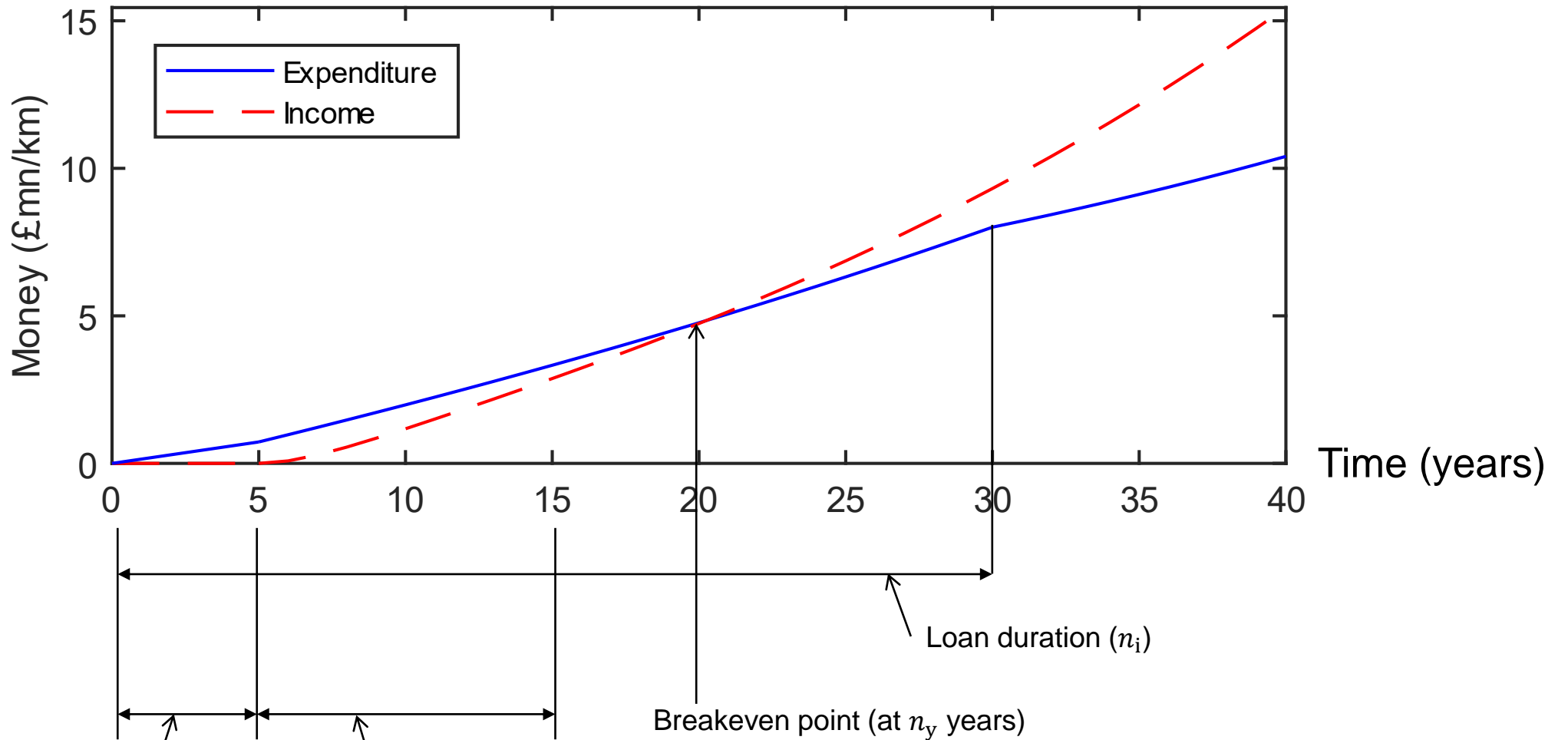


1<sup>st</sup> generation 40t BEVs are ~£300k...  
A large portion of this is battery cost!

# **An ERS economic model for any country**

# ERS cost breakeven model

Money in/out for maximum number of trucks ( $n_T$ ) = 3000/day



Construction time ( $n_c$ )

98% usage ramp-up time ( $n_r$ )

Parth Deshpande et al. (2023), "A breakeven cost analysis framework for electric road systems", Transportation Research Part D: Transport and Environment, 103870.

# ERS cost breakeven model

- Aim: To determine **number of trucks** required for **cost breakeven**

- For 1 km of ERS:

- Expenditure:

- Infrastructure (£2m) on loan
- Maintenance (5%)

- Profit:

- Electricity selling (7p/kWh)
- Depends on number of trucks

$$Q_T = \frac{e_{tr} n_T n_d}{E_T}$$

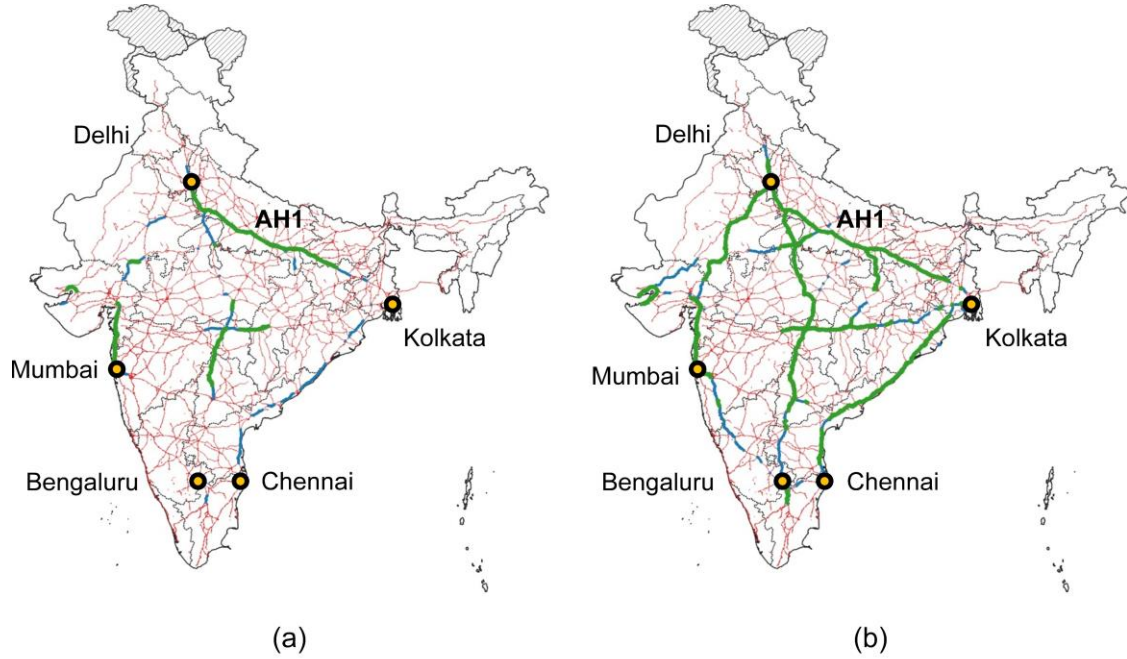
Annual freight flow (t/year)  $Q_T$  =  $\frac{\text{Energy transferred per vehicle (kWh/km)} \times \text{Max. number of trucks (1/day)} \times \text{Number of days of ERS usage (days/year)}}{\text{Energy efficiency of freight (kWh/t-km)}}$

^ In terms of freight flow

$$n_T = \frac{C_{ERS} \left[ n_y \frac{r_i(1+r_i)^{n_i}}{(1+r_i)^{n_i} - 1} + f \left( \frac{(1+r_z)^{(n_y-n_c)} - 1}{r_z} \right) \right]}{\frac{\Delta r_e}{100} e_{tr} n_d \left( 1 - e^{\frac{-4(n_y-n_c)}{n_r}} \right) \left( \frac{(1+r_z)^{(n_y-n_c)} - 1}{r_z} \right)}$$

Capital cost of ERS (£/km)  $C_{ERS}$   
 Number of years for breakeven  $n_y$   
 Annual loan instalment fraction  $r_i$   
 Annual maintenance cost fraction  $f$   
 Number of years for ERS construction  $n_c$   
 Sum of inflation terms over  $(n_y - n_c)$  years  $r_z$   
 Maximum number of trucks  $n_T$   
 Electricity profit margin (pence/kWh)  $\Delta r_e$   
 Energy transferred per vehicle (kWh/km) (= Max. power / average speed)  $e_{tr}$   
 Number of days of ERS use per year  $n_d$   
 Number of years for 98% ERS usage  $n_r$   
 Ramp-up curve for number of trucks using the ERS  $r_z$

# Country results



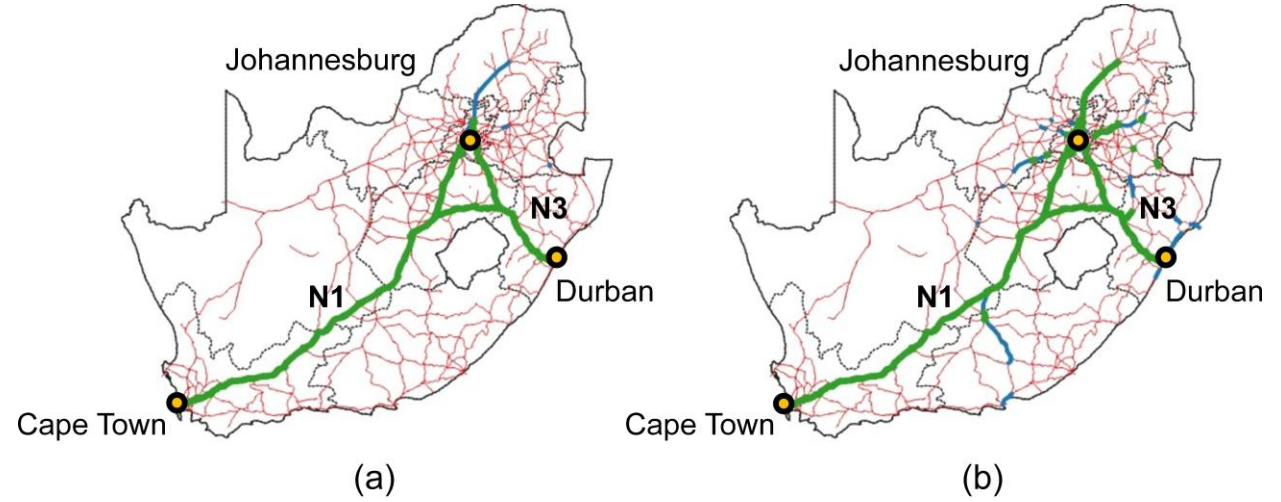
India

Breakeven duration

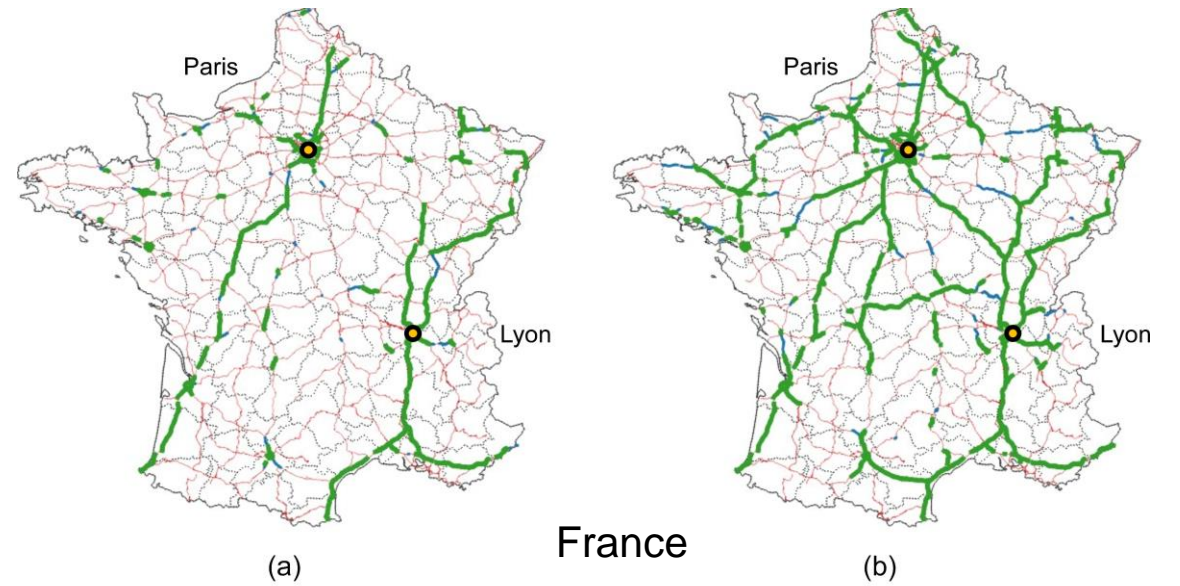
— < 20 years

— 20 - 30 years

— > 30 years



South Africa



France

# Conclusions

# Conclusions

- ERS is the lowest cost and emissions solution for decarbonising HGVs in the UK
- This is backed by robust economic modelling and simulation studies
- The driving cycle simulation model has assessed the real-world “on-the-ground” implications for UK logistics
- An investment model suitable for all countries has been developed (requires HGV traffic data)
- UK announcement on UK ZERFD ERS trial...?



## Funding



Innovate  
UK

## Collaborators



ARUP



SIEMENS



Possible.

Thank you!

Contact:  
[chris@zeuslabs.com](mailto:chris@zeuslabs.com)

